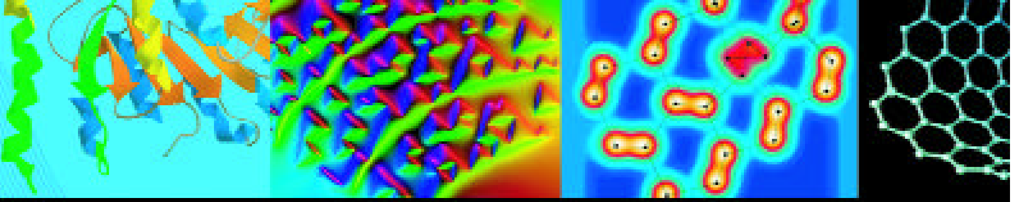

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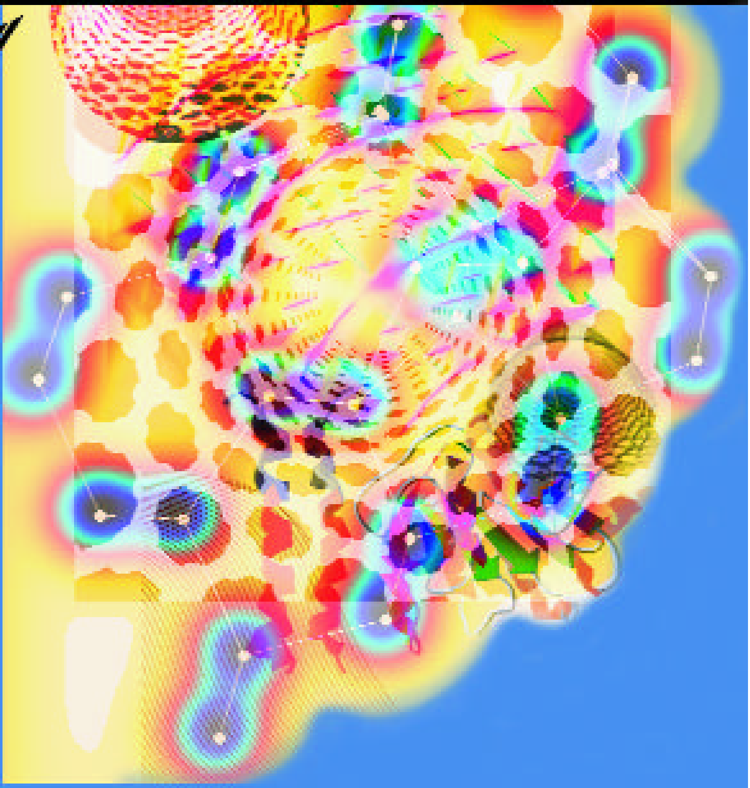

Sustaining the Information Technology Revolution

American Institute of Physics' Corporate Associates
2004 Meeting Report

Including the Academic-Industrial Workshop

October 24-26, 2004 ◆ Yorktown Heights, NY

Hosted by IBM T. J. Watson Research Center

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To serve the industrial physics community by improving the effectiveness of people and organizations in advancing corporate goals through the use of physics.

2004 INDUSTRIAL PHYSICS FORUM REPORT

Sustaining the Information Technology Revolution

October 24-26, 2004, Rye, New York

In the past few decades, information technology (IT) has grown rapidly to become a major component of the world economy. Basic research in solid state physics laid the foundation for this growth, and ever since, physicists have played a leading role in the invention and development of the devices of IT. With the growth has come a great broadening of the very meaning of IT. Computers, once the property of national governments and large corporations, now entertain our children. With the industry increasingly focused not on the hardware, but on new products and services enabled by that hardware, what role will physicists play in the continuing IT revolution?

Certainly much of the current excitement surrounding nanotechnology is based on the prospect of new devices to process, store and communicate information. Physicists will continue to make leading contributions in the pursuit of "smaller, faster, cheaper." At the same time, developments such as the birth of quantum information theory and the ongoing "informatization" of biology suggest that the reach and meaning of IT will continue to broaden. Physicists are well-positioned to help lead the emergence of the truly ubiquitous information technology that so many have predicted, according to speakers at the 2004 Industrial Physics Forum, hosted by IBM's T.J. Watson Research Center and held in Rye, New York, October 24-26.

About IBM

IBM's T.J. Watson Research Center is IBM's headquarters for its global research activities. About 3000 scientists and engineers work at eight laboratories in six countries to support IBM's core business. The company's interests span all areas of IT, from physics and chemistry to cognitive science to research in business applications. IBM researchers invent new materials and device structures and integrate these components into exciting machine designs and architectures. They create tools and technologies that will enable the continued evolution of computing and computing services. Their research is often done in concert with colleagues in academic and government research centers, as well as in the marketplace with customers who provide challenging research problems. Cutting-edge physics research continues to be a primary focus for IBM, according to Armando Garcia, vice president of technical strategy and worldwide operations. "More than ever before, innovation will be critical to sustaining leadership and competitiveness in the IT industry," he said.

Theme Session:

Sustaining the Information Technology Revolution

Paul Horn, IBM's senior vice president of research, kicked off the conference theme session on sustaining the information technology revolution. "IBM has continued to reinvent itself to sustain and grow at a time when the capability of the core technology has changed by 15 orders of magnitude," he said. "You can't be in an industry like that without embracing change." He outlined three key elements that are critical to IBM's success.

First, the company seeks to embrace disruptive technologies. Over the years, IBM has moved from mainframe computers to personal computers, and from mainframe software to distributed software. It is now moving into open source software: the production of software by public communities of developers who contribute code to an evolving product. Second, IBM takes advantage of new market opportunities. The company shifted from hardware to software, and is now focusing on services. Finally, innovation has always been valued at IBM. "Innovation is so critical to how companies are trying to differentiate themselves," said Horn. "It's not just invention: innovation occurs at the intersection of invention and insight. It's the application of the invention."

Information technology is evolving too rapidly for the old model of technology transfer, so new models are needed. "The last thing you want is to be a stand-alone corporate R&D department," Horn said. "That model has failed repeatedly. The goal is to be first with the best technology: that's where you find the profit and market value." For instance, IBM employs a joint program model in which the technology team stays with the work all the way from idea to product on the market. The company believes it is critical to have an innovative environment, a diversity of viewpoints, and to be able to create opportunities for interdisciplinary brainstorming, because breakthroughs happen at those interfaces. It is also vital to embrace risk. IBM invested $200 million to build Blue Gene, the world's most unique, fastest computer, in what was essentially a five-year long-term exploratory wager: could the company build a high-power computer with a fraction of the floor space and outlet power? IBM succeeded, and in the process created a new paradigm for how computing is done, according to Horn.

Companies must embrace risk, pursue innovation, and disrupt their own outdated business models before their competitors do so, in order to maintain market leadership in the IT industry.

Randy Isaac, vice president of IBM's strategic alliances, systems and technology group, gave a brief historical overview of the microelectronics industry, stressing the impact of the physical sciences on the microelectronics industry. The industry has come a long way since its birth in 1904 with the invention of the first vacuum tube rectifier. The invention of the transistor led to the introduction of the first microprocessor in 1971, resulting in decreasing costs of computation. Much of the enabling science for this revolution came out of fundamental physics research in areas such as lithography, in semiconducting and insulating materials, and in devices like the transistor.

Lithography is a technique for defining a pattern on a wafer and it is the dominant factor in determining how many transistors manufacturers can fit onto a single chip. Thanks to the use of increasingly shorter wavelengths of light, lithography has passed its supposed limit of 1 micron by more than an order of magnitude to achieve dimensions below 90 nm. Isaac believes that optical lithography will continue through 2008-2010 using deep UV light, but the industry needs to continue research to explore future replacement candidates, such as extreme UV, x-ray lithography, and electron-beam lithography.

Samuel Stupp, Board of Trustees Professor of Materials Science, Chemistry and Medicine at Northwestern University, discussed his interdisciplinary research in supramolecular chemistry and biology. He noted that a recent report on the National Nanotechnology Initiative, sponsored by the National Academy of Science, contained two particularly interesting recommendations. Specifically, the report called for an increase in multiagency investments in research at the intersection between nanoscale technology and biology, as well as strong support for the development of an interdisciplinary culture in nanoscience. “Biology is an example of what nanotechnology should be,” said Stupp. “Nature operates with highly orchestrated and adaptive interactions among self-replicating and self-assembling nanostructures that control behavior both at the microscopic cellular level and the human macroscale.”

Self-assembly in supramolecular chemistry takes advantage of the fact that order can emerge from disorder at any length scale with little human effort. At the very core of nanotechnology is a bottom-up approach to the design of fundamental structures; making small molecules that are “programmed” to produce functional nanostructures. For example, self-assembly of large biomolecules could be used to grow wires that weave 2D or 3D networks. Self-assembling polymers can emulate collagen’s extra-cellular matrix. In the area of medicine, there is the possibility of constructing an artificial matrix to manage cell behavior for the regeneration of tissue. This would open up the possibility of heart tissue regeneration after a heart attack, recovery from severe spinal-cord injuries, the ability to grow new teeth, better repair of bone fractures, and cell therapies for diabetes. Such a technique could even minimize stroke dysfunction through the repair of neurons in the brain.

The convergence of physical sciences, information sciences and biology offers several new business opportunities, according to Caroline Kovac, general manager of

IBM Healthcare and Life Sciences, which had a humble beginning but brought in over $1 billion in annual revenues in 2003. One critical area for future growth is the evolution and transformation of medicine with new technology. "It's not just about the basic science of biology: it's about the evolution and ultimately the transformation of how medicine is practiced," said Kovac. She envisions a future health care system that is quick to adopt new information technology, as well as new imaging and diagnostic techniques, such as sensors and implantable devices based on nanotechnology. For example, the medical research community is developing a Bluetooth-enabled (wireless) shirt that measures the body's vital signs, and an implantable information device to monitor blood sugar levels in diabetics.

The challenges currently facing the medical industry include developing new, more effective drugs, faster and more cheaply; improving the effectiveness, safety and cost of medical care through better diagnostics, treatment, and organizational efficiency; translating molecular biological research into medical care; and understanding biological systems with predictive models using large-scale computer simulation. The latter is an especially good area for physicists and biologists to collaborate: using the tools of "systems biology" to build complex computational models, and also devising data and image analysis algorithms for pattern discovery.

Kovac foresees a new world of information-based medicine and new treatment options that will lead to a revolution in clinical practice. The first step is data integration: gaining access to diverse heterogeneous distributed data, such as the National Digital Mammography Archive, which is a direct result of physicists' work on developing "grid" networks. Biobanks are a key source of the phenotypic information necessary to conduct research on the genetic factors involved in disease. One example of a biobank is the controversial D-CODE project in Iceland. If additional such databases existed, the pharmaceutical industry might be aided in its pursuit of new drugs targeted to specific patient populations. For example, CYP450 is an enzyme that regulates how fast drugs are metabolized in the bloodstream, and genetic factors affect its expression in various individuals. If a person metabolized drugs faster, they would need a higher dose than someone who metabolized the drug more slowly. Genetic typing for CYP450 expression may allow optimum personalized dosing of many prescription drugs, reducing unwanted side effects

Interdisciplinary culture in science is a key element for a bright future in novel technologies. But it is the individual scientist who needs to have an interdisciplinary brain, not just a diverse team that makes it work.

New device structures are needed to maintain performance as we get closer and closer to atomic scale sizes in integrated circuits, according to David DiVincenzo, a research scientist at IBM. "We need to think about new ways, other than CMOS, of doing information processing," he said. A quantum computer exploits quantum phenomena, such as superposition and entanglement, to perform operations on data. In a classical computer, data are measured by bits. A bit is the fundamental carrier of information in a computer; it exists in one of two possible states "0" or

"1". A quantum computer would use "qubits", which can be in a superposition of states, where both 0 and 1 are possible components but the full state is described by a wave function. Experiments have already been carried out in which quantum computational operations were executed on a very small number of qubits.

While the potential for quantum computing is huge and recent progress is encouraging, commercial quantum computers are still many years away. Many technologies are currently being explored. For instance, IBM scientists have demonstrated simple quantum computing experiments using nuclear magnetic resonance (NMR), an approach that led to the development of fundamental tools that can be used in many future types of quantum computers. Most important of these was a way to simulate and predict the signal degradation caused by 'decoherence'—unintended quantum fluctuations—thus minimizing errors.

IBM is now developing new quantum computing systems that can more easily "scale" to the large numbers of qubits needed for practical applications. Strong candidates today include electron spins confined in semiconductor nanostructures (often called quantum dots), nuclear spins associated with single-atom impurities in a semiconductor, and electronic or magnetic flux through superconductors. The first quantum computing applications would likely to be co-processors for specific functions, such as solving difficult mathematical problems, modeling quantum systems and performing unstructured searches. Quantum cryptography is another potential application area. It provides means for two parties to exchange an enciphering key over a private channel with complete security of communication. If someone "eavesdrops" on the data stream, he or she will alter the photons in that stream, alerting the two parties that the code has been compromised.

Laboratory Tours

On Monday afternoon, attendees toured IBM's T.J. Watson Research Laboratories in Yorktown Heights, NY. All conference participants had the opportunity to see IBM's signature Blue Gene/L SuperComputer, currently the world's fastest computer, as well as the company's latest advances in quantum computing and scanning SQUID microscopy, especially efforts to produce nanoscale SQUID sensors with greatly enhanced sensitivity. The company has also developed a mouse adapter for people who suffer from hand tremors that interfere with their ability to use a computer mouse.

Participants then split into three separate tours. One group focused on IBM's work in chemical self-assembly and in biology, particularly systems biology and large-scale computer simulation of biological systems.

A second group focused on materials and devices, most notably recent advances in IBM's Magnetic Random Access Memory (MRAM), in which thin film deposition is used to deposit magnetic tunnel junctions onto electronic substrates. IBM has also recently fabricated the world's densest static random access memory (SRAM) using electron beam lithography. Participants who selected the second tour option also learned about the electronic and electro-optic applications of carbon nanotubes, most notably their incorporation into field-effect transistors.

The third tour featured advances in optics and photonics, such as Picosecond Imaging for Circuit Analysis (PICA), a technique that gathers the faint infrared light emitted by switching transistors to detect faults in the functioning of complex circuits. IBM has also developed a femtosecond laser technique for repairing the photomasks used in lithography for patterning silicon chips, and a scanning transmission electron microscope, which is helping scientists to better understand the physics of interfaces and materials. Finally, the tour showed the company's engagement in developing silicon integrated nanophotonics, a technology for the dense integration of tiny photonic circuits that will be able to manipulate light signals in the same way that electrical signals are currently manipulated in computer chips.

Policy Session:
Society, Economics, and Information Technology

George Scalise, president of the Semiconductor Industry Association (SIA), opened Tuesday morning's policy session exploring the connections between society, economics and information technology. Scalise based much of his commentary on the conclusions and recommendations of a recent report from the Presidential Council of Advisors on Science and Technology (PCAST) on maintaining a competitive edge in IT and manufacturing. Scalise chaired the PCAST subcommittee that produced the report. In particular, Scalise cited the critical role played by semiconductors in establishing U.S. leadership in practically every major technology developed over the last 20 years or so.

In an era where corporate outsourcing is cause for concern, some 70% of U.S.-owned wafer fabrication facilities are located in the U.S. Roughly 27% of sales are in the U.S., and 55% of the silicon industry's worldwide employment is based in the U.S. Global sales of semiconductor chips are expected to be more than $100 billion in 2004. Across other industries, the picture isn't quite so rosy. The PCAST report found that the manufacturing share of GDP and employment has halved over the last 50 years, although productivity has increased and output has remained steady. Improvements in IT drive fully one-half of the economic growth of the U.S. and two-thirds of its productivity gains. "It's not enough for the U.S. to be good today, what's important is how good we are going to be tomorrow," said Scalise. "We've had a good run, but can we maintain that into the future?"

PCAST is also concerned by the increasing ability of foreign competitors not just to manufacture commoditized products cheaply, but also to develop their own innovative new products and industries. Government subsidies are not the answer, either for the IT industry or the manufacturing sector. Instead, the focus should be on enhancing the university R&D base in the U.S., improving S&T education, and the development of related workforce skills. Scalise spoke in support of ongoing efforts to double the budget of the National Science Foundation, pointing to the European Union's recent decision to increase basic research funding from 2% to 3% of its GDP. "We need to keep up to compete," he said. He favors making the recently extended Congressional tax cuts for R&D investment permanent. Scalise also cited the need for even more tax incentives to "preserve the viability of stock options" and enhance the U.S. entrepreneurial climate.

Scalise cited the need for "unquestioned superiority" in nanotechnology, biotechnology, information science and engineering. Nanotechnology is of particular interest to the IT industry, which expects existing CMOS technology to reach its limits within the next 10-15 years. "There is a 15-year gap between the latency period from research to production [of new technologies]," said Scalise, adding that the time to focus on developing alternatives is now. The new Nanotechnology Research Initiative (NRI) is a joint effort between industry, academia and the federal government to pave the way for innovations in nanotechnology. The NRI's objectives include establishing five interdisciplinary R&D centers in the U.S. and developing a "road map" for nanoelectronics, including the development of next generation devices, materials, tools and manufacturing techniques.

The IT market is increasingly consumer-driven, thanks to popular devices such as cell phones, digital cameras and DVD players, and Scalise expects those trends to continue, with an even greater need for lower power and lower cost. "In the 1980s, very few of U.S. would have predicted the unique convergence in the 1990s that produced the Internet revolution," said Scalise, who believes that almost everything we own in the future will have electronic components, all networked together. "I believe that kind of convergence will continue."

Maintaining a thriving R&D manufacturing environment and "innovation ecosystem" are the keys to assuring continued U.S. leadership in the IT industry. The big winners are those who develop talent, techniques and tools so advanced that there is no competition.

Dale Jorgenson, S.W. Morris University Professor at Harvard University, discussed the past and future impact of IT on the world economy. In his view, the nature of our economy has changed with the rise of information technology. In the information age, the mantra is "faster, better, cheaper," and the role of IT impacts IT prices and the cost of capital investments. The recent American growth resurgence since 1995 based on IT investment and the resulting growth in productivity has served as a catalyst to bring IT to the attention of macroeconomists, who are seeking to translate IT prices into an accurate measure of what value IT puts into the economy. However, "Our picture of IT is incomplete," said Jorgenson. While economists have tracked semiconductor and computer price indices since around 1985, they still lack common equipment price statistics, and apart from pre-packaged software, there are no statistics on software.

For instance, it is critical for economists to combine input shares of IT with capital contributions to gain an accurate picture of the economies at work. IT accounts for only 5% of the nation's GDP, but that 5% accounts for 46% of all input of investment into the U.S. economy, according to Jorgenson. Since 1965, the IT industry has followed Moore's Law: the number of transistors on a chip doubles every 18-24 months. There were 2300 transistors on a chip in 1965; the Pentium 4 was released November 20, 2000, and had 42 million transistors. If the airline industry, for example, had sustained this kind of growth, it would be equivalent to being able to fly today from New York City to Paris in about 14 seconds. While exponential growth may not be sustainable, Jorgenson believes that a 3.6% growth rate is sustainable as the technology continues to improve. Strong growth prospects are not limited to the U.S.: every industrialized country has some growth prospects, although local conditions may differ.

The world of business has been transformed by information technology and the old management models no longer apply, according to Marv Adams, chief information officer for the Ford Motor Company. Specifically, fairly predictable business systems have become complex. "For big institutions to thrive in the future, we must create more partnerships between industry and academia and develop better management models," he said. "It's hard to break very old patterns of management, but it must be done." $2 billion to $3 billion in annual IT related expenses. He estimates that by 2012, 40% of the cost of a new car will derive from embedded technology. A simpler, predictable infrastructure is needed in the automotive industry to cope with these changes. The old model is based on simple rational decision-making and monitoring. New models from science and mathematics are required to manage this complexity.

Adams believes one possible solution lies in the field of chaos theory and nonlinear systems. He defined a chaotic system as a "complex system of interdependent agents, each employing strategies that alter the probability of future events." By that standard, IT is a nonlinear system. "There is a staggering rate of change in IT that results in agent strategies constantly adapting," he said. For example, it used to take months for hackers to design viruses to exploit IT system weaknesses; it now takes a few days, or even just a few hours, within publication of a vulnerability. New models and strategies are needed to respond to virus threats more quickly. "We can't eliminate complexity, and we can't predict it, but we can better manage and harness complexity," he said.

In order to implement such a model, companies must reduce the degree of variation in their operations. Too much variation can push the system beyond the zone of "rich complexity" into the purely chaotic realm. Companies must balance this with the need to provide enough structure to enable productive interaction. Finally, management must minimize amount of top/down hierarchical command and control structure. For decision-making in a complex environment, a bottom-up approach, in which the best selections rise to the top, is preferable. Unfortunately, Adams estimates that only 5% of management today is qualified to operate in the complexity zone; most find it uncomfortable. "It's all about finding the balance point: too much order versus not enough order," said Adams. "The idea is to nudge the system right to the edge of chaos into the complexity zone."

Large institutions must embrace new, more complex business models drawn from physics and mathematics if they are to thrive in the future economic environment. This will require strong partnerships between business and the sciences to develop a wide range of approaches and the competency to know which models to apply, and when.

Barbara Simons, a consulting professor in science, technology and society at Stanford University, maintains that voting is a bona fide national security issue. She specifically addressed the challenges presented by the new electronic voting machines, used broadly for the first time in the November 2004 presidential election. Congress passed the Help America Vote Act (HAVA) in 2002, earmarking almost $4 billion for new voting equipment to replace the outdated punch card and lever machines by the 2004 election, although there is a waiver for some states until 2006. But according to Simons, she and many other computer experts have serious concerns about the security of all-electronic voting machines, including bug-plagued software and the risk of malicious code affecting election outcomes. For this reason, numerous public interest groups are now demanding voter verifiable paper trails to verify that their ballots have been correctly recorded. It should also be possible to conduct a recount, if necessary.

Among Simons' chief concerns is the fact that the voting machine software used for the 2004 elections was the intellectual property of the companies supplying the machines, taking control of the results away from election officials. Instead, the officials must rely on the company's computer experts to verify that the correct software is being used. Voting machine manufacturers did finally agree to submit portions of their code to the National Software Reference Library maintained by the National Institute of Standards and Technology in Gaithersburg, MD, but they did not submit source code or any subsequent patches. Election security remains compromised as long as the testing and debugging procedures are so inadequate, according to Simons and her fellow experts.

Complicating matters is the fact there is more than one type of electronic voting machine. For example, paperless voting machines use touch screens for users to cast their votes. Other machines keep the touch screen aspect but print out paper ballots so that voters can check that their vote was accurately recorded. Optical scan voting machines read paper ballots marked with a Number 2 pencil, much like the standardized tests students take in schools. It is the paperless machines that are the cause of greatest concern. In one type of machine, an employee could easily commit vote fraud simply by inserting unauthorized code into the finished product, and it would be impossible for election officials to detect the attack. Until these concerns are adequately addressed, Simons believes that paper ballots are the only foolproof method for recording votes. And she dismisses those who believe that it's just too hard to accurately count paper ballots: "Banks count paper every day. It's a well-established technology."

"We can declare success in the IT revolution: we won," said Neil Gershenfeld, director of MIT's Center for Bits and Atoms, who kicked off the Frontiers in Physics session. Rather than debating how to maintain that revolution, he believes the IT industry should shift its focus to the next pending technological revolution: fabrication for the masses that allows them to create, not just consume products. Gershenfeld designed a course, "How To Make (Almost) Anything," initially to train students to be his lab assistants, but it quickly expanded in popularity to include even those students with lesser technical skills who'd always dreamed of being able to design and fabricate something. He allowed them to hijack million-dollar machines that would otherwise have been inaccessible to them.

One student designed his own bicycle with a custom frame inspired by a Picasso painting. Another one made a "Scream Body" device, which stores screams of frustration until it's appropriate to let them out. Still others designed the Interpet Explorer, a Web browser for parrots, and an alarm clock that requires the user to wrestle with it in order to prove the user is awake. Finally, a female student designed a dress lined with sensors that cause the dress to flare out when someone gets too close, protecting her personal space. This approach, says Gershenfeld is "the killer application" for the future of personal computing: project-based, just-in-time, peer-to-peer manufacturing. Students were using the equipment for their wants, not their needs—he calls it "design and marketing for one, the personalization of technology." Consumers can email their own design schemes around the globe so the product can be reproduced on site, with no need for physical shipping. "This is state-of-the-art fabrication. There's a tremendous demand, we just need to fill it by giving the general public access to those capabilities," he said.

Michael Turner, assistant director of mathematical and physical sciences at the National Science Foundation, gave an update on the "dark side of the universe": the mysterious dark matter and dark energy that makes up most of the universe. Ordinary matter accounts for a mere 4% of all the matter in the universe. It is the dark matter that holds the universe together, accounting for 33% of all matter in the universe. And the dark energy determines the density of the universe, accounting for 66% of total matter in the universe. Scientists introduced the notion of dark matter when astronomers realized that the galaxies were moving at very large speeds and there just wasn't enough star mass to account for it. Then, in 1998, two separate teams of physicists discovered that instead of gradually slowing down, the expansion of the universe is speeding up. Scientists believe that there has to be an exotic form of dark energy to account for this.

"Dark energy may be the most profound question in cosmology today because it is at the nexus of a number of other critical questions," said Turner. In fact, the ultimate fate of the universe rests on whether the dark energy is constant or changing. If the dark energy remains constant, the acceleration will continue indefinitely, and matter will grow farther and farther apart. Within a hundred billion years, we will only be able to see a few hundred galaxies, compared to the hundreds of billions we can see today. If the dark energy decreases over time, expansion could slow enough for the universe to recollapse in a Big Crunch. And if the dark energy increases its expansion rate over time, it could rip apart every galaxy, star and atom in the universe within 100 billion years. Scientists call this "the Big Rip." Thus far, the dark energy appears to be constant.

The growing degree of automation in biology requires a "natural successor" to integrated circuit parallel computing, capable of increasing automation throughput rates by at least an order of magnitude, according to Stephen Quake, a professor of physics and applied physics at the California Institute of Technology. He believes the answer lies in microfluidics technology, specifically the lab-on-a-chip commercial assays that were introduced in the 1990s for DNA sequencing, among other applications. The next step is to develop microfluidic technology that would allow several different functions to be integrated on a single chip. "Right now everything is a bottleneck—people's ambitions are outstripping their capabilities," he said. "These could be relieved by making things smaller with microfluidics."

Quake's CalTech team has developed a set of microfabricated valves and pumps. Valves are the equivalent of ICs in biology. The valves are made out of soft silicone rubber (the same material used in bathtub caulking and for contact lenses) using a technique called "soft lithography" that is similar to the injection molding used to manufacture toys. Using this technique, he has built microfluidic chip arrays with as many as 6000 microvalves and up to 1000 individual tiny chambers. The channels in the devices are less than 100 microns in width (the width of a human hair) and use the same pumping mechanism found in human intestines. He also developed a separate device with more than 2000 microvalves that enables a scientist to perform two distinct assays in two separate chambers. "We now have the tools in hand to design complex microfluidic systems," said Quake, who predicts that his chips will have 100 times the number of cells and valves within a few years. The technology is being commercialized by a San Francisco-based company called Fluidigm, for such applications as DNA sequencing and protein crystallization.

Carbon nanotubes are likely to be the "wonder material of the 21st century,"according to Phaedon Avouris, IBM Fellow and Manager of Nanoscience and Nanotechnology, IBM Research, who closed the session with a look at IBM's work on building electronic and optoelectronic devices with carbon nanotubes. Potential applications range from ultrathin waterproof fabrics, to flat panel displays for TVs and computer monitors. In fact, researchers have already built transistors, diodes, light emitters and detectors out of carbon nanotubes. Because of the unique nature of carbon at the nanoscale, all these functions can be achieved using a single device, simply by altering the voltages applied.

Carbon nanotubes are also a highly attractive potential replacement technology for silicon circuits. "An electronics industry based on nanotubes could preserve a lot of what's good about existing silicon technology—the logic circuits and much of the manufacturing process—but base it on new materials that get around the majority of problems that would probably doom any attempts to make extremely small CMOS devices," said Avouris. Much of his work at IBM is focused on building field-effect transistors with nanotubes, since they are the basic building blocks of CMOS integrated circuits. Carbon nanotubes can also emit and detect light, and IBM scientists have exploited this property to build the first single-molecule, electrically controlled light source. The next step will be to integrate these various carbon nanotube devices into complex integrated circuits. These will become the building blocks of a new generation of nanoscale ICs.

> The Frontiers in Physics session aptly demonstrated how interdisciplinary research at the interfaces of biology, physics and other scientific fields could one day lead to revolutionary advances to ensure that the current revolution in Information Technology continues in the future.

The 2005 Industrial Physics Forum will be hosted by the National Institute of Standards and Technology, November 6-8, 2005, in Gaithersburg, MD. The theme will be built around physics and advanced measurement technology.

2004 ACADEMIC-INDUSTRIAL WORKSHOP

Engineering Education and Student Performance-Based Review

A Pre-Conference Workshop of the Industrial Physics Forum

October 24, 2004, Rye, New York

Professionals representing educational and research careers in academic, industry and federal facilities gathered on October 24, 2004, in Rye, NY, for the 2004 Academic-Industrial Workshop, held in conjunction with the annual Industrial Physics Forum of the American Institute of Physics (AIP). Jack Hehn, director of education at AIP and workshop host, welcomed participants, then said that the annual workshop is intended to stimulate dialog between industrial and academic leaders on subjects of mutual importance to them and to the physics community.

There were two main thrusts to the day's discussions on engineering education and student performance-based review: first, physics currently has no accreditation process, although nationally, the physics curriculum is very homogenous. Does physics need accreditation? And is accreditation a good method for assessing student performance? Engineering does have an accreditation process through ABET, Inc. In recent years, questions have been raised by educational researchers as to whether it is even possible to accurately measure student performance.

The day was organized into three sessions, each followed by smaller breakout group discussions. Since one of the principal goals of the workshop is professional networking, the subsequent small group discussions are designed to encourage interaction among the participants as they each offer their personal expertise and experience with regard to various aspects of the educational and research enterprises, and to glean new insights from this exchange of perspectives.

KEYNOTE:
ACHIEVING EXCELLENCE IN ENGINEERING EDUCATION

Norman Fortenberry kicked off the workshop with a keynote address outlining the major challenges currently facing engineering education in light of major shifts in the social, political and economic environment. Fortenberry is director of the Center for the Advancement of Scholarship in Engineering Education (CASEE), a large-scale initiative founded by the National Academy of Engineering in 2002. He began by pointing to disturbing indicators that student interest in engineering is now declining, after holding steady for almost 40 years.

For example, a 2004 report by the National Science Board found that universities in China, Japan, South Korea, and Taiwan together produced over 400,000 engineers in 2001, compared to 110,000 for the four largest European nations and 60,000 for the U.S. The same trend can be seen at the doctoral level: foreign students earned 49% of all engineering degrees awarded by American universities in 2000. In fact, across the board in scientific and engineering disciplines, student interest is decreasing. There is an attrition rate of 50% from freshman to senior year in undergraduate engineering departments. “We can do better in retention, not just acceptance. Students are voting with their feet, choosing other disciplines,” said Fortenberry. “We need to find better ways to engage prospective students.”

CASEE is intended to foster excellence in engineering education, and create a more productive and responsive engineering workforce by building bodies of knowledge, supporting communities of scholars and promoting diffusion of research. The center does this though academic and industrial affiliates (its membership currently includes 31 organizations and 28 distinguished individuals), fellowships, and scholarships. Tools under development include a web portal linking various publications on education research across disciplines. The portal is intended to strengthen the research base. CASEE is also building a “what works” clearinghouse to translate educational research into practice, since many innovations in this area are not broadly disseminated..

CASEE affiliates are engaged in four key areas of education-related research. First, there are studies of how to improve how engineering is taught, learned, and assessed. Also under investigation are mechanisms to enhance the diversity of engineering students. Other affiliates are looking at ways to strengthen how engineering knowledge is organized and transmitted via courses, textbooks, and learning technologies. Finally, there are studies under way about how to better encourage widespread use of educational innovations.

Ultimately, "We need the actual involvement and help of those in [the] social and educational sectors to tackle these issues," said Fortenberry. "So we want to study teaching and learning, teachers and learners (the human factor) as well as the tool set (curriculum), stakeholder goals, plus external constraints. They all work together, so we must understand all these factors to improve the system."

Physics and engineering educators must bring the same rigor to education now applied to technological advances, and incorporate relevant knowledge from other disciplines, to ensure the continued vitality not just of physics and engineering, but of all related scientific fields.

SESSION I:
DRIVING EDUCATIONAL EXCELLENCE

The first session focused on driving educational excellence. Fred Berry, head of the ECE Department at the Rose-Hulman Institute of Technology, provided some context for the day's discussions by outlining the history of electrical and computer engineering, dating back to 1882, when the Massachusetts Institute of Technology offered its first electrical engineering course. Since the 1940s, curriculum requirements for engineering programs have vacillated between emphasizing the "softer" skills like communication and interpersonal relations, and the traditional "hard" scientific approach, with an emphasis on science and technology. Most recently, in 1994, there was a push for educational reform, leading to the establishment of many coalitions for creating innovation in engineering education. This included new curriculum models that were more integrated and focused on open-ended problem-solving using multidisciplinary skills. A year later, ABET issued its "Vision for Change," establishing new guidelines for 2000 to revise the minimum standards for engineering accreditation.

Despite these changes, accreditation doesn't meet the needs of every engineering program. According to Berry, one of strongest current trends is a rise in Bachelor of Arts degrees in engineering, instead of the traditional Bachelor of Science degrees. No accreditation is required so students can tailor their degrees to meet specific needs. The BA is designed as a professional degree for those who go on to medical or law school, for example. The fastest growing new engineering degree is a BA in engineering, followed closely by a BA in bioengineering. "These new BA degrees provide students with the ability to enter a practicing profession and are broad enough to enable them to pursue careers in other professions," said Berry. In fact, he maintains that by 2013, most students will earn many different master's degrees over the course of two or three different careers, rather than focusing on one career path for their entire working life. “So now we have conflicting trends: generic undergraduate engineering programs versus targeted undergraduate engineering degree programs to meet the needs of industry,” said Berry. However, he believes that industry is coming to realize that a broad engineering degree will meet their needs, and this will eventually eliminate the need for a wide range of specialized degrees.

“Our curricula are changing rapidly in light of new technologies and teaching methods,” said Berry, who believes that any new curriculum requirements must produce technically competent workers, first and foremost, by way of a rigorous foundation in math, science and engineering science, plus traditional electrical engineering and computer engineering topics. But they should also include a fundamental development of a second language, an understanding of professional practice, and should provide as many elective opportunities as possible. The degree should be an interface between science and engineering to shorten the transition from discovery to invention and application.

In order to achieve the lofty goal of genuine educational and curriculum reform, there is a corresponding need for a bona fide research journal to disseminate the research results of the growing U.S. community of engineering education scholars. Jack Lohmann, associate provost and professor of industrial and systems engineering at the Georgia Institute of Technology, described how the Journal of Engineering Education (JEE) has been transformed from a broad scholarly journal to one focused on education research. In the mid 1980s, engineering education emerged as its own discipline arising from the growing recognition that how we teach is as important as what we teach. Even today, Lohmann estimates that only 1 in 7 engineering faculty members are skilled in education research. “We need to build a bigger community and encourage more faculty to approach education and curriculum innovations with the same scholarly rigor as they do their technical research,” he said.

JEE’s origins date back to 1893, and the journal has gone through many incarnations since its inception to meet constantly changing needs. In November 1991, it was split into two parts: PRISM became the trade magazine for society communication on behalf of the American Society for Electrical Engineering (ASEE), while JEE was repackaged as a scholarly journal for innovations. The initial focus was on curriculum innovations but today the focus is on new knowledge, or research. “In the past, many papers highlighted interesting improvements but were not research because they didn’t assess student learning or performance in a measurable scientific way, whereas scholarly research papers pose important questions and then build on relevant bodies of knowledge, before presenting results based on compelling evidence,” said Lohmann.

In January 2005 JEE will unveil its latest new vision. It is now more than just a vehicle for published articles: it is intended as a means of building a vibrant community of scholars. According to Lohmann, the editorial board strives for a combination of high-quality articles and first-class operations, including a clear statement of purpose. It publishes its review criteria and strives to provide both thoughtful and timely reviews. JEE has achieved its goal of getting 90% of received manuscripts reviewed within four months from submission. In 2001 only 17.5% of manuscripts met that criteria, and from January to June, 2004, 100% of submitted manuscripts were reviewed within two months. These improvements should help vault JEE into the pre-eminent world-class journal for engineering education research.

The continued vitality of such fields as engineering and physics depends upon a vibrant community of scholars advancing the frontiers of knowledge through research. How faculty teach is just as important as what they teach.

SESSION II:
PERFORMANCE—ABET AND THE WORKPLACE

The second session focused on the issue of how best to assess student performance and prepare engineering students for the workforce. Duane Abata, past president of the American Society for Engineering Education and a member of ABET's review board, defined engineering as "a matter-of-fact profession, applying the fundamental laws of physics to produce a practical end product or service." Currently, obtaining an undergraduate degree in engineering requires courses in math, physics, and chemistry, combined with hands-on laboratory experience, preferably from an accredited program. Engineers can be licensed on a state-by-state basis; Abata suggested a national licensure program to ensure uniformity in proficiency requirements.

Why does the field of engineering require accreditation and licensure? According to Abata, engineering evolved during the industrial revolution from skilled trades, like machinists and toolmakers. Early engineering educators sought to distinguish themselves from the trades by instituting a rigid set of criteria, and established accreditation as an attempt to standardize programs nationwide. By 1980, virtually all worthy programs were accredited. For most of the 20th century, ABET—as the accrediting agency—employed a so-called "bean counting" form of assessment, focusing largely on mechanical auditing and distribution of credits over required areas. When ABET introduced new, reformed guidelines for 2000, the need for auditing was significantly reduced, although specific program criteria still remained. But one aspect of the process has remained constant: obtaining accreditation is a long and involved process. An institute must request a site visit to assess the candidate program, followed by a report and subsequent visit by an accreditation team. A final report and a declaration are made after the ABET board meets.

Abata outlined several benefits to be gained from accreditation, including maintaining uniform minimum standards for degree programs. Standards are becoming internationally recognized, which promotes mobility in engineers' careers. Furthermore, it helps establish a degree program's credibility, which is critical to obtaining financial support for engineering colleges within universities. But there are drawbacks. The strict criteria that accompany accreditation can limit students and teacher creativity, as well as the diversity of programs offered. ABET has tried to address this concern by incorporating continuous assessment as an integral part of the process, allowing for corrective action to fix problems. There is also a higher cost, in both money and time, to achieving and maintaining accreditation.

IBM's director of corporate university relations, Margaret Ashida, rounded out the session with a corporate view of science and engineering education as preparation for the workplace. For her department at IBM, the priority is collaboration with academic departments to develop the technical talent pipeline by making IBM technologies available to faculty for use in the classroom. "Students need to develop the skills required by on-demand business," she said. So IBM launched the Academic Initiative in 2004 to deepen its partnerships with academia. The company is pursuing research with selected institutions and seeking to accelerate the recruitment of the best talent for future innovation, which will ultimately help the company increase sales.

Ashida sees a pronounced shift towards services at IBM in the past few years. "The nature of innovation is changing," she said, moving beyond the invention of new technologies to an emphasis on how to solve real-world problems to achieve economic growth. "We've already seen the paradigm shift from invention to innovation, from linear ways of thinking to more dynamical approaches." U.S. leadership in innovation is increasingly at risk, however. China currently leads the world in the number of science and engineering students it produces: 20 million versus about 15 million in the U.S. In 1983 about 61% of all physics papers published in scientific journals came from U.S. authors; today that percentage is closer to 29%.

Achieving true innovation requires the fusion of three components: exploratory computing technology; integration of hardware, software and services into an open computing technology; and offering business value through services and software to improve business performance. Every project at IBM now has some aspects of all three, according to Ashida. Diversity is also a key business priority: IBM wants to foster inclusiveness and accessibility. More and more corporations are focusing on the "services revolution": trying to be bilingual in business and technology and fostering a multidisciplinary capability. Because of the rapid pace of change in the 21st century, lifelong learning is required to remain competitive. IBM's new motto is, "Working together to help create in-demand skills for an on-demand world." Said Ashida, "Our technology is an ecosystem, and we are hurting ourselves by closing our borders. Education needs to be as global as technology."

The need for standardized accreditation criteria in engineering must be balanced with allowing sufficient freedom to foster creativity for students to be truly competitive. Creative innovation is now the key to achieving success in the workplace.

Session III:
Physics and Engineering Collaborations

The third session focused on innovative examples of collaborations between physics and engineering, offering two different approaches as examples. David Campbell, dean of engineering at Boston University and editor of AIP's journal *Chaos*, outlined some of the introductory physics course reforms undertaken at the University of Illinois/Urbana-Champaign (UIUC). In May 1995, several engineering departments at UIUC began threatening to drop one of three semesters of introductory physics to make room for additional courses they needed to meet ABET accreditation criteria. There was also an internal dissatisfaction within the physics department: specifically, there were problems with faculty burnout and poor student assessments in the elementary physics sequence. The old model followed the tradition of large, non-interactive lectures and smaller sections for discussions and labs, but the latter were often intellectually disconnected or displaced in time from the lectures and each other. Exams consisted of quantitative problems, with no testing of students' grasp of the actual concepts.

Given release time from teaching to develop a new approach, a cadre of physics faculty came up with a new model that emphasizes concepts, not just calculational results. "The students weren't learning physics under the old model, they were learning how to manipulate equations," said Campbell. "But learning is not a spectator sport; students must be involved." Thus, the new model employs active learning methods, including peer instruction. Courses are team taught and the labs are integrated with the lecture course so that students learn to predict, observe, and explain experiments. "Team teaching reduces burnout and means there are no "heroes" or "stars", so that the success of the department doesn't rest on a single individual," said Campbell. There are also Web-based interactive homework assignments, and one-third of exam questions are conceptual, with the rest being calculational in nature. Importantly, the new approaches were based on demonstrated results from Physics Education Groups at several institutions across the country. There is now a body of irrefutable evidence that these new pedagogical techniques are more effective in retaining student interest and conveying key concepts in a lasting way than the prior approaches.

According to Campbell, student attitudes have changed dramatically for the better since the new model went into place in the fall of 1996. He outlined some reasons why the new model is working so well. For instance, the process of designing a new curriculum model was a collective faculty effort, and there was strong administrative support for systemic change. What would it take for the same model to work elsewhere? First, the organization has to recognize the need for change, and want to change. Ironically, faculty members are often the major obstacle to change: for instance, a professor often feels he or she "owns" the course, when in fact the department owns the course. "We need to listen to students and be willing to learn from others, for example, by reading up physics education research," said Campbell. There is also a broader cultural issue that acts as a barrier to change. Overcoming such obstacles was a "tremendously liberating" experience for the faculty at UIUC, said Campbell.

Steve Cobb, chair of the physics and engineering department at Murray State University, believes there are some major challenges facing physics and engineering programs in the U.S.: declining enrollments, low retention and graduation rates; and an unappreciative employment sector. In the mid 1970s Murray State University (MSU) began promoting physics-based programs with a much broader appeal to combat such trends. The concept used a "physics plus" approach: physics and computer science, or medicine, business, or engineering. But in the mid 1990s enrollments began declining again, and this time MSU responded by seeking ABET accreditation. "We wanted our students to be able to perform well in areas where traditional science and engineering disciplines overlap," said Cobb.

Cobb outlined several benefits to be gained by seeking accreditation. First, it establishes accountability in the curriculum, faculty obligations, student expectations, alumni input and employer preferences. Second, the curriculum benefits from the design, fabrication and testing exercises, such as designing and building and testing a water-propelled car. Accreditation brings national recognition to a program and increases its appeal to good students. MSU has seen its enrollment increase as a result of ABET accreditation, although this growth occurred at the expense of traditional physics majors. And the university now has increased partnerships with industry, giving their students expanded placement opportunities, with a corresponding increase in entry-level salaries. It has also expanded student opportunities for graduate school, and for obtaining professional licensure.

While this cannot be considered a physics program, Cobb reported that the model is nonetheless working for MSU. And their students can definitely compete in the workplace with those who have more traditional physics degrees. Student placement rates after graduation are essentially 100%. But there are downsides to MSU's course of action. Upper level physics courses are taught less often, and the number of physics majors has declined. The department has also lost complete control, since they are technically accountable to an outside agency (ABET) to maintain accreditation, and ABET criteria must be satisfied. It is essential to have good faculty and clerical support, since the amount of documentation required can be overwhelming. There are also significant costs associated with accreditation, and program assessment is mandated. Despite this, "A physics foundation with an engineering emphasis is, for MSU, the best of both worlds," says Cobb.

There are many different models available for curriculum reform and there is no such thing as "one size fits all." Each department must assess its own unique attributes and corresponding needs when devising new programs and standards for courses.

Breakout Groups:
Consensus and Summary

Recruitment and retention of engineering majors is one of the most pressing issues facing the field; industry is looking for more than the next Einstein, it desires liberal arts-educated engineers. Educators, however, are concerned that the trend of many different kinds of engineering degrees will ultimately lead to the balkanization of the field. This trend is forcing engineering to redefine itself and decide upon what is most fundamental. Thus far, the consensus seems to be on promoting design and a systems approach to problem-solving.

Faculty must have the freedom to focus on education issues so that their students can benefit from new teaching methodologies innovation. Retention is higher with these new teaching methods. Students might not learn any less or any more, but they enjoy the classes more, and thus will more willingly put more time into physics or engineering. "Don't try to change the students to fit the system, because you can't," one participant commented. "Rather, ask how much you can change the system to attract more students without compromising standards of excellence?"

Others contended that educators in physics and engineering need to convince prospective employers that they are getting some added value when they hire U.S. graduates to justify the higher salaries, particularly when such businesses can get the same skill set for much less overseas. Innovation of ideas is the critical component, and thus universities must also foster key elements of entrepreneurship to bring innovation to the market. There is also a need to address the problem of under-represented minorities in physics and engineering: diversity is another important aspect of fostering innovation.

For their part, departments can offer instruction that is more tied to the real world, more interdisciplinary, and that better meets the needs of different constituents. Such instruction must be consistent within the department and not idiosyncratic to the individual faculty. As for the curriculum, we must bring in the industrial experience through internships, for example, at the high school level, and not just for the most gifted students. This requires large-scale investment by the federal government and industry in both innovation and revising the curriculum.

The sixth annual Academic-Industrial Workshop will be held on Sunday, November 6, 2005 at the National Institute of Standards and Technology in Gaithersburg, MD. The theme will be built around communicating the "broader impact" of science and the role of scientists in explaining their work to citizens, students, decision-makers, or taxpayers.

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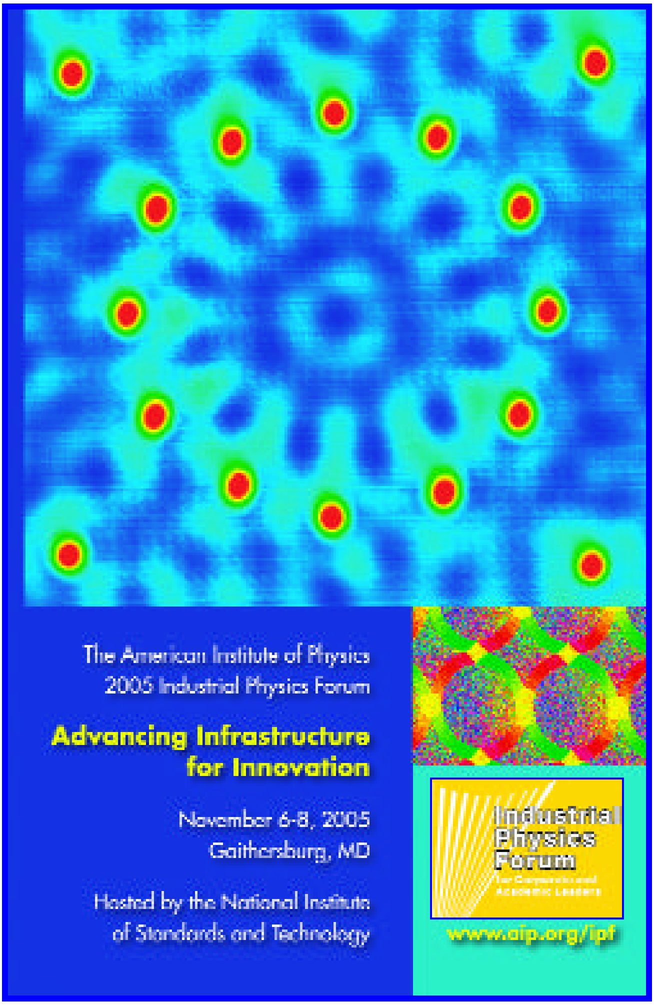

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